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► To cite this version:

P. Bernstein, C. Picard, Stéphane Flament, N. Beaudet, J. Hamet, et al.. High Tc Superconducting Flux Flow Transistors: Potential Performances and Problems. Journal de Physique IV Proceedings, 1996, 06 (C3), pp.C3-373-C3-379. 10.1051/jp4:1996357 . jpa-00254275

HAL Id: jpa-00254275

<https://hal.science/jpa-00254275>

Submitted on 1 Jan 1996

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High T_c Superconducting Flux Flow Transistors: Potential Performances and Problems

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1. INTRODUCTION

Superconducting Flux Flow Transistors (SFFT) are devices including one or several microbridges in which the nucleation and the motion of vortices can be controlled by the magnetic field generated by the current I_{com} circulating in a near-by control line (see Fig. 1a and 1b). Large band amplifiers with a very high cut off frequency and very fast logical operators were demonstrated at Sandia National Laboratories a few years ago [1]. However the complete reproduction of these results in other laboratories has not been achieved at our knowledge (see [2], [3], [4] and [5] for examples). In this paper, from the computation of the critical current modulation due to the magnetic interaction between the different current lines of a SFFT, we propose an estimation of the potential current gain of these devices as a function of the number of included microbridges and we discuss the causes of the encountered problems.

Figure 1 : (a) Single bridge SFFT and axes orientation (b) Multi-bridge SFFT

2. MAGNETIC INTERACTION BETWEEN CURRENT LINES

In the Meissner state, the circulation of magnetic field vector $\vec{B}$ along a path (C) drawn around a microbridge and perpendicular to bias current I_b (see Fig.2) can be written :

$$\mu_0 \times I_b = 2x \left| \int_0^w B_y(y,0) dy \right| + \int_1^0 B_z(0,z) dz + \int_0^t B_z(w,z) dz \quad (1)$$

with :

$$2x \left| \int_0^w B_y(y,0) dy \right| = \beta \times \mu_0 \times I_b \quad (0 < \beta < 1) \quad (2)$$

β can only be determined with numerical computation from the minimization of the system energy.

Figure 2 : Integration path (C) of vector **B** around a microbridge

We can write :

$$\int_t^0 B_z(0,z)dz + \int_0^t B_z(w,z)dz \approx t \times [\langle B_z(0,z) \rangle + \langle B_z(w,z) \rangle] = \mu_0 \times (1-\beta) \times I_b \quad (3)$$

On the other hand, we assume that :

i) vortices are nucleated when along both edges of the microbridge the modulus of the sum of the self and external magnetic field is simultaneously equal to the threshold value B_N . This assumption is written :

$$\langle B_z^*(0,z) \rangle + B_{ez}(0) = -B_N \quad (4a)$$

$$\langle B_z^*(w,z) \rangle + B_{ez}(w) = B_N \quad (4b)$$

B_{ez} is any external applied field to the microbridge and $\langle B_z^*(0,z) \rangle$ and $\langle B_z^*(w,z) \rangle$ are the values of $\langle B_z(0,z) \rangle$ and $\langle B_z(w,z) \rangle$ at the transition from the Meissner to the mixed state.

ii) vortex pinning is negligible. As a consequence the measured critical current corresponds to the first vortex nucleation. From (3) and the set of equations (4) it can be written :

$$\left| \langle B_z^*(0,z) \rangle \right| + \left| \langle B_z^*(w,z) \rangle \right| = 2 \times B_N = \mu_0 \times \frac{(1-\beta)}{t} \times I_{cro} \quad (5a)$$

when no external field is applied and :

$$\left| \langle B_z^*(0,z) \rangle \right| + \left| \langle B_z^*(w,z) \rangle \right| = 2 \times B_N - [B_{ez}(w) - B_{ez}(0)] = \mu_0 \times \frac{(1-\beta)}{t} \times I_{cr} \quad (5b)$$

when an external field is applied. I_{cro} and I_{cr} are the critical current values without and with an applied external field respectively. From (5a) and (5b) we have :

$$I_{cr} - I_{cro} = \frac{t}{\mu_0 \times (1-\beta)} \times [B_{ez}(0) - B_{ez}(w)] \quad (6)$$

Let us consider the magnetic interaction between two similar neighbouring bridges (see Fig.3).

Figure 3 : Magnetic interaction between two neighbouring bridges. B_b^A and B_b^B are self bias fields due to currents I_A and I_B respectively. B_n^A and B_f^A are the contributions of the field due to current I_A circulating in A to the perpendicular component of the field along respectively the neighbouring and the far edge of bridge B

We assume, as an approximation, that in the Meissner state the perpendicular component B_b^A of the self bias field at the edges of bridge A is given by :

$$|B_b^A| \approx \frac{|B_b^A(0)| + |B_b^A(w)|}{2} = \frac{\mu_0 \times (1-\beta)}{2xt} x I_A \quad (7)$$

The contribution of the field due to current I_A circulating in A to the perpendicular component of the field along respectively the neighbouring and the far edge of bridge B can be written :

$$B_n^A = k_n \times \frac{\mu_0 \times (1-\beta)}{2xt} x I_A \quad (8a)$$

and :

$$B_f^A = k_f \times \frac{\mu_0 \times (1-\beta)}{2xt} x I_A \quad (8b)$$

with :

$$0 < k_f < k_n < 1 \quad (8c)$$

k_n and k_f are coupling factors which depend on the inhomogeneous current distribution in bridge A and on the distance between bridge A and the neighbouring and the far edge of bridge B respectively. From Eq.(6) to (8) the critical current modulation of bridge B due to the current in bridge A can be written :

$$I_{cr}^B(I_A) - I_{cr}^B(0) = \Delta I_{cr}^B \approx \frac{t}{\mu_0 \times (1-\beta)} \times (B_n^A - B_f^A) = \frac{k_n - k_f}{2} \times I_A = \frac{k^*}{2} \times I_A \quad (9a)$$

with :

$$0 < k^* < 1 \quad (9b)$$

It is important to note that ΔI_{cr}^B does not depend on β (if the current lines are similar).

3 - CURRENT GAIN OF SFFT's

3.1 Single bridge SFFT's

In the case of a single bridge SFFT we have to take into account the field created by the control current only (Fig.1a). If we define the current gain as the ratio of the bridge critical current modulation to the control current we have :

$$G = \frac{\Delta I_{cr}}{I_{com}} = \frac{k^*}{2} < 0.5 \quad (10)$$

The current gain of a single bridge SFFT is always less than 0.5.

3.2 Multibridge SFFT's

The magnetic field acting upon a bridge in a multibridge SFFT is due to the current in the control line and to the current circulating in the other bridges of the device. For the sake of simplicity, we shall take into account the interaction between neighbouring bridges only. However we shall distinguish the coupling factor between bridges k_p from the coupling factor between the control line and the nearest bridge k_c . On the other hand, in the Meissner state, the magnetic flux in each hole of the device is not allowed to change. As a result the current circulating in each bridge is the sum of the bridge bias current and shielding currents. The shielding currents are given by the set of equations :

$$L_{p,p+1} \times I_{Sp,p+1} + \sum_{j=p} M_{j,j+1}^{p,p+1} \times I_{Sj,j+1} = -\phi_{p,p+1} \quad (11)$$

$L_{p,p+1}$ is the self inductance of the loop around the hole located between bridges p and $p+1$, $I_{Sp,p+1}$ and $I_{Sj,j+1}$ are the shielding currents which circulate around the hole located between bridges p and $p+1$ and j and $j+1$ respectively, $M_{j,j+1}^{p,p+1}$ is the mutual inductance between loop $(j, j+1)$ and loop $(p, p+1)$ and $\phi_{p,p+1}$ is the magnetic flux in hole $(p, p+1)$ generated by the bias currents flowing in the bridges of the device and the current in the control line or due to external sources. As a result the bridge currents of a n -bridges SFFT can be written (see Fig.4 for the case of a 3-bridges device) :

$$I_{T1} = I_1 + I_{S1,2} \quad (12a)$$

$$I_{T2} = I_2 + I_{S2,3} - I_{S1,2} \quad (12b)$$

$$\vdots$$

$$I_{Tp} = I_p + I_{Sp,p+1} - I_{Sp-1,p} \quad (12c)$$

$$\vdots$$

$$I_{Tn} = I_n - I_{Sn-1,n} \quad (12d)$$

I_{Tp} and I_p are the total current and the bias current in bridge p respectively. As a result the SFFT total current is equal to the bias current flowing through the device. We have :

$$I_T = \sum_{p=1}^n I_{Tp} = \sum_{p=1}^n I_p \quad (13)$$

At the transition to the mixed state the total current circulating in each bridge is equal to the bridge critical current.

3.2.1 2-Bridges SFFT's

In the case of a 2-bridges SFFT, from (9a) it can be written :

Figure 4 :Diagram of the bias and shielding currents circulating in a 3-bridges SFFT according to the model

$$I_{cr1} - I_{cr0} = \frac{1}{2} \times [k_c \times I_{com} + k_p \times I_{cr2}] \quad (14a)$$

and :

$$I_{cr2} - I_{cr0} = \frac{1}{2} \times k_p \times I_{cr1} \quad (14b)$$

I_{cr1} and I_{cr2} are the critical currents of bridge 1 and 2 respectively ; I_{cr0} is the critical current of a single bridge with no magnetic interaction. From (13) and the solution to this set of equations, the SFFT critical bias current I_{crT} can be written :

$$I_{crT} = I_{cr1} + I_{cr2} = \frac{4 \times I_{cro}}{2 - k_p} + \frac{k_c \times I_{com}}{2 - k_p} \quad (15)$$

The maximum value for I_{crT} with no current in the control line ($I_{com} = 0$) is obtained for $k_p = 1$. We have :

$$I_{crT \max} = 4 \times I_{cro} \quad (16a)$$

The current gain is :

$$G = \frac{k_c}{2 - k_p} \quad (16b)$$

The maximum value for G is obtained for $k_c = k_p = 1$. We have :

$$G_{\max} = 1 \quad (16c)$$

3.2.2 *n*-bridges SFFTs

In the case of a SFFT with n bridges, with the same assumptions as above, at the transition to the mixed state we have :

$$I_{cr1} - I_{cro} = \frac{1}{2} \times [k_c \times I_{com} + k_p \times I_{cr2}] \quad (17a)$$

$$I_{cr2} - I_{cro} = \frac{1}{2} \times k_p \times [I_{cr1} + I_{cr3}] \quad (17b)$$

$$I_{crq} - I_{cro} = \frac{1}{2} \times k_p \times [I_{crq-1} + I_{crq+1}] \quad (17c)$$

$$I_{crn} - I_{cro} = \frac{1}{2} \times k_p \times I_{crn-1} \quad (17d)$$

The solution to this set of equations and the corresponding I_{crTmax} and G_{max} values are given in table I for $3 \leq n \leq 6$.

TABLE I

Total critical current I_{crT} , maximum ratio $\frac{I_{crT}}{I_{cro}}$ of the total critical current to the critical current I_{cro} of a single bridge and maximum current gain G_{max} for a SFFT with n bridges.

n	I_{crT}	$\frac{I_{crTmax}}{I_{cro}}$	G_{max}
3	$2 \times I_{cro} \times \frac{2k_p + 3}{2 - k_p^2} + \frac{1}{2} \times k_c \times I_{com} \times \frac{k_p + 2}{2 - k_p^2}$	10	1.5
4	$4 \times I_{cro} \times \frac{k_p + 4}{4 - 2k_p - k_p^2} + k_c \times I_{com} \times \frac{2}{4 - 2k_p - k_p^2}$	20	2
5	$I_{cro} \times \frac{k_p^2 - 16k_p - 20}{3k_p^2 - 4} + \frac{1}{2} \times k_c \times I_{com} \times \frac{k_p^2 - 2k_p - 4}{3k_p^2 - 4}$	35	2.5
6	$8 \times I_{cro} \times \frac{6 + 2k_p - k_p^2}{k_p^3 - 4k_p^2 - 4k_p + 8} + k_c \times I_{com} \times \frac{4 - k_p^2}{k_p^3 - 4k_p^2 - 4k_p + 8}$	56	3

It is seen that the maximum current gain increases by 0.5 for each additionnal bridge. On the other hand it is interesting to observe that the critical current of a device with n bridges is larger than n times the critical current of a single bridge. This effect is unexpected ; how important is it when the number of bridges is large? With $I_{com} = 0$, the addition of the equations of set (17) yields :

$$I_{crT} = n \times I_{cro} + k_p \times \left[\sum_{q=2}^{n-1} I_{crq} + \frac{1}{2} \times (I_{cr1} + I_{crn}) \right] \quad (18a)$$

with :

$$I_{cr1} = I_{crn} \quad (18b)$$

from symmetry considerations. As a result we have :

$$I_{crT} = n \times I_{cro} + k_p \times [I_{crT} - I_{cr1}] \quad (19)$$

If n is large it can be written :

$$I_{crT} \gg I_{cr1} \quad (20)$$

and we have :

$$I_{crT} = \frac{n \times I_{cro}}{1 - k_p} \quad (21)$$

As a result a strong $\frac{I_{crT}}{I_{cro}}$ ratio can be expected for a large k_p value. k_p depends critically on the separation between the bridges which, however, cannot be made arbitrarily small because the sum of the shielding currents in a bridge must not exceed the bridge critical current.

4. PROBLEMS AND PROSPECTS

The main difficulty encountered with SFFT's is the pinning of vortices. Pinning induces a decrease in the vortex flow which results in a strong decrease in the dynamic resistance of the device. Moreover if the vortices are pinned, the measured critical current corresponds not to vortex nucleation but to vortex depinning, which is almost insensitive to the effect of the magnetic field generated by the control current. As a result the transresistance is almost zero. We have compared vortex dynamics in identical microbridges with different thicknesses and structures (mono and multilayers). Preliminary results, which will be published in the near future, show that the effect of an external applied field is stronger and the range of vortex motion between two pinning centers is larger on thin films than on thicker ones. We have observed also important effects due to the nature of the substrate and the structure of the device.

CONCLUSION

We have shown that if pinning is low, magnetic coupling between current lines make possible to obtain a current gain larger than unity with SFFT's. Moreover the current gain is seen to increase as a function of both the coupling factor between the control line and the first bridge and the coupling factor between bridges. As a result the gain of the device is very sensitive to its design, especially to the separation between lines. An unexpected result is that if this separation is small, the critical current of a device with n bridges is much larger than n times the critical current of an isolated bridge. The main obstacle to eliminate in order to make high performance devices is the strong pinning which is seen to affect high T_c oxide superconducting films. The future of SFFT's will depend upon the solution to this problem.

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